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Lagrangian-Eulerian Approach to Modeling Contaminants

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Edited by
Mohammad Karamouz, Polytechnic University, Brooklyn, New York
George R. Baumli, International Boundary and Water Commission, El Paso, Texas
William J. Brick, U.S. Army Engineer District, San Francisco, California

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Lagrangian-Eulerian Approach to Modeling Contaminants[1]

John F. Paul[2], Henry A. Walker[3], and Jean A. Nocito[4],M. ASCE

A Lagrangian-Eulerian modeling approach predicts potential contaminant distributions resulting from the disposal of sewage sludge at the Deepwater Municipal Disposal Site off the northeast United States continental shelf. The Lagrangian aspect involves Monte-Carlo simulations of particle trajectories to determine solids concentrations. The Eulerian aspect is the calculation of contaminant distributions using the Eulerian convective-diffusive equation.

Introduction

The Deepwater Municipal Disposal Site (DMDS), which is the eastern 343 square-kilometer strip of the 106-Mile Ocean Disposal Site, is located off the northeast United States continental shelf, approximately 120 nautical miles from the entrance to New York Harbor (Figure 1). This site is designated on a five-year interim basis for the disposal of municipal sludge (EPA, 1984a), with disposal operations having begun on March 22, 1986. The site is to be used by municipalities from New York and New Jersey which currently use the 12-Mile Site in the New York Bight. These municipalities must phase-out operations at the 12-Mile Site by December 1987 due to the termination of sludge disposal at that site (EPA, 1984b). Predictions of potential contaminant distributions resulting from sludge disposal at DMDS are required to (1) assess permit applications and (2) design a monitoring program to be implemented after full-scale disposal operations commence.

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[2]Chief, Exposure Assessment Branch, Environmental Research Laboratory, U.S. EPA, Narragansett, Rhode Island 02882

[3]Research Environmental Scientist, Exposure Assessment Branch, Environmental Research Laboratory, U.S. EPA, Narragansett, Rhode Island 02882

[4]Physical Scientist, Science Applications International Corporation, South Ferry Road, Narragansett, Rhode Island 02882

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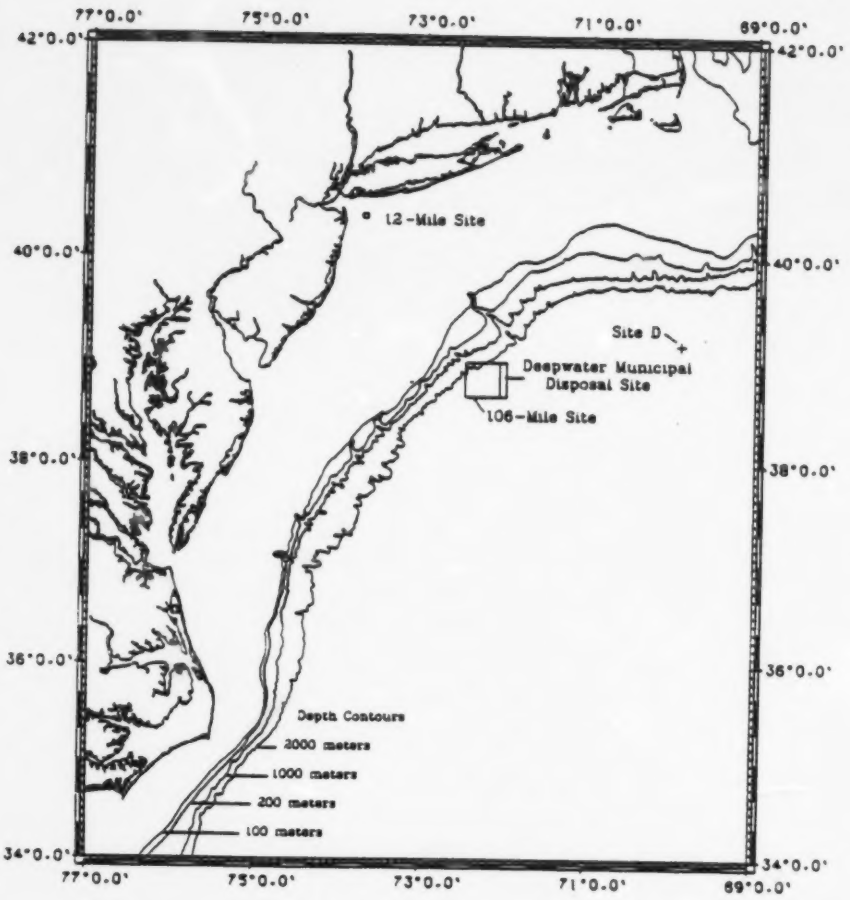

Figure 1. Location of Deepwater Municipal Disposal Site off Northeast United States Continental Shelf.

Background

Physical oceanography in the vicinity of DMDS makes this site distinctly different from coastal sites in the area which might be potentially impacted by disposal operations. The site is nominally two orders of magnitude deeper than

typical coastal sites. Also, it is not clear how much, if any, material would deposit on the bottom sediments before entrainment into the Gulf Stream off Cape Hatteras. It has been estimated that up to 20 percent of the disposed material (sludge) might deposit over a 25,000 square kilometer area downstream of the site (O'Connor et al., 1983). For these reasons, we have chosen to investigate the potential contaminant distributions on a horizontal spatial scale ranging from tens to hundreds of kilometers. Distributions on a smaller spatial scale are primarily controlled by the actual mechanics of the disposal operation.

Previous work on sludge disposal at DMDS provided upper-bound estimates on contaminant distributions in the upper mixed layer of the water column (Paul et al., 1986; Walker et al., 1986). Due to simplifying assumptions, the sludge contaminants were treated as completely conserved in the upper mixed layer. Thus, the analysis was reduced to a two-dimensional horizontal view. The probabilistic nature of the currents was used to make predictions of long-term, time-averaged contaminant distributions. Disposal of material at the site was treated as discrete two-dimensional Gaussian plumes which were transported by mean currents and dispersed by the variance-covariance structure of the currents.

Below we describe the procedure used to extend our previous two-dimensional work to include the vertical dimension. The probabilistic distribution of settling characteristics of the sludge particulates is used to determine vertical movement of the material in the water column. Once the particulate distribution is known, we can determine the resultant steady-state, long-term contaminant concentrations for both the dissolved and particulate phases.

Summary of Approach

Our approach is divided into Lagrangian and Eulerian aspects. We first calculate particulate concentrations in a Lagrangian frame of reference by determining particle trajectories. We then switch to an Eulerian frame of reference to calculate the dissolved and particulate phases of the sludge contaminants.

Lagrangian Aspect

To account for the probabilistic nature of currents that exist off the U.S. continental shelf, we conduct Monte-Carlo

simulations of particle trajectories originating at the disposal site using the distribution of currents as determined from long-term current meter moorings at Woods Hole Oceanographic Institution's (WHOI) Site D (Figure 1). Data from current meters, deployed at various depths in the water column, provide the horizontal movement of trajectories. Table 1 illustrates the mean and variance-covariance structure for currents measured at WHOI Site D. Figure 2 shows the autocorrelation of the cross-shelf component of surface currents at this site.

Vertical movement of trajectories is determined from the probabilistic distribution of sludge particulate sizes, in conjunction with the particulate and sea water densities. Figure 3 is an example of sludge settling velocities as determined by Faisst (1976). Synthesis of a large number of independent particulate trajectories provides steady-state solids concentrations in a Lagrangian frame of reference resulting from sludge disposal.

If we assume that all of the contaminants in sludge were bound on solids, we could directly determine contaminant distributions from the solids distribution. This would be counter to the assumption that all sludge contaminants are dissolved in the water (Paul et al, 1986; Walker et al, 1986). However, individual contaminants in the sludge are actually partitioned between the particulate and dissolved phases. To improve on an upper-bound estimate, we must explicitly investigate both phases of the contaminants.

Eulerian Aspect

To calculate contaminant distributions for dissolved and particulate phases, we must first transform from the Lagrangian analysis used to calculate particle trajectories to an Eulerian frame of reference. This provides the steady-state solids concentration as a function of space in an Eulerian framework.

The Monte-Carlo simulations described above provide both the effective mean velocity and dispersion in a Lagrangian framework produced by the currents. However, we require the mean velocity and dispersion (effective diffusion) in the Eulerian frame of reference to determine contaminant distribution. Mean velocity is determined by time-averaged movement of the ensemble of particle trajectories. Dispersion is calculated by an inverse procedure using the Eulerian convective-diffusive equation, specifying mean velocity and the Eulerian distribution of the solids

Figure 2. Autocorrelation of Cross-Self Surface Current (54m depth) at WHOI Site D.

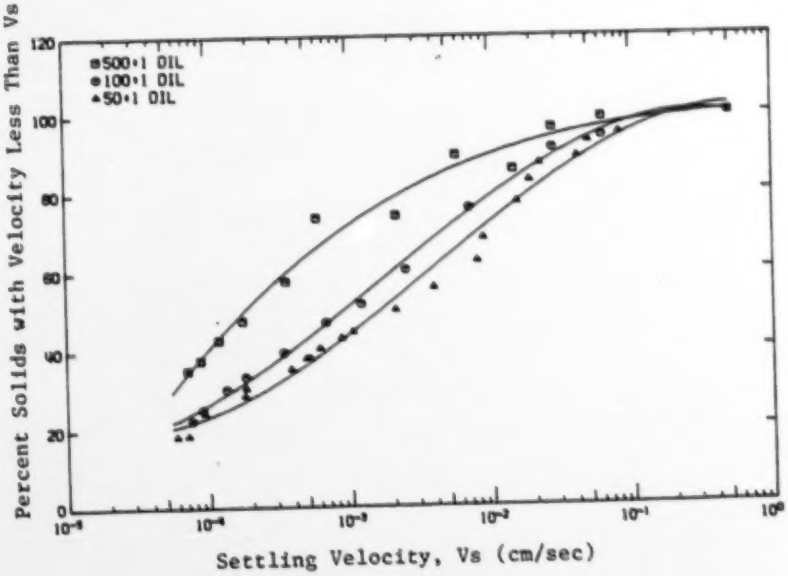

Figure 3. Settling Characteristics of Los Angeles County Sludge-Seawater Mixture at Three Dilutions (after Faisst, 1976).

concentration. That is, we solve the following equation for diffusion, D:

$$\frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} + \frac{\partial wS}{\partial z} = \frac{\partial}{\partial x} D \frac{\partial S}{\partial x} + \frac{\partial}{\partial y} D \frac{\partial S}{\partial y} + \frac{\partial}{\partial z} D \frac{\partial S}{\partial z}, \quad (1)$$

where t is time, x and y are the horizontal coordinates, z is the vertical coordinate, u and v are the mean currents in the horizontal directions, w is the velocity in the vertical direction, and S is the solids concentration. We assume that dispersion of the contaminants and solids are generated by currents, and thus diffusion of contaminants is identical to that calculated for solids from equation (1).

Determination of dissolved and particulate phases of the contaminants is accomplished using equilibrium partitioning theory to solve the convective-diffusive equation for total contaminant concentration. That is, we solve the following:

$$\frac{\partial uC_t}{\partial x} + \frac{\partial vC_t}{\partial y} + \frac{\partial wC_p}{\partial z} = \frac{\partial}{\partial x} D \frac{\partial C_t}{\partial x} + \frac{\partial}{\partial y} D \frac{\partial C_t}{\partial y} + \frac{\partial}{\partial z} D \frac{\partial C_t}{\partial z} - \lambda C_t, \quad (2)$$

$$C_t = C_d + C_p, \text{ and} \quad (3)$$

$$K_p = \frac{C_p}{C_d S}, \quad (4)$$

where C_t is the total contaminant concentration, C_d is the dissolved contaminant concentration, C_p is the particulate contaminant concentration, K_p is the equilibrium partition

coefficient, and λ is the decay coefficient for the contaminant.

Summary

We present a procedure that is employed to estimate three-dimensional contaminant distributions resulting from disposal of sewage sludge at DMDS off the northeast U.S. continental shelf. Previous work treated contaminants as being completely dissolved and provided upper-bound estimates for the upper mixed layer of the ocean. Predictions of the three-dimensional distributions provide more realistic estimates for the entire water column and allow for contaminant flux to the sediments. It is expected that the major cumulative impact of sludge disposal would occur in the sediments.

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Table 1. Mean and variance-covariance structure of currents measured at WHOI Site D.[1]

Depth of current meter (meters)	Mean vector (cm/sec) $\begin{bmatrix} \text{east} \\ \text{north} \end{bmatrix}$	Variance-covariance matrix ((cm/sec)^2) $\begin{bmatrix} \text{east} & \text{east-north} \\ \text{east-north} & \text{east} \end{bmatrix}$
54	$\begin{bmatrix} -12.33 \\ 1.12 \end{bmatrix}$	$\begin{bmatrix} 249.77 & -47.07 \\ -47.07 & 257.50 \end{bmatrix}$
206	$\begin{bmatrix} -11.51 \\ 0.16 \end{bmatrix}$	$\begin{bmatrix} 172.20 & -32.89 \\ -32.89 & 161.61 \end{bmatrix}$
1008	$\begin{bmatrix} -4.52 \\ -0.93 \end{bmatrix}$	$\begin{bmatrix} 47.90 & 3.30 \\ 3.30 & 40.65 \end{bmatrix}$
2063	$\begin{bmatrix} -5.27 \\ -0.62 \end{bmatrix}$	$\begin{bmatrix} 45.78 & -5.49 \\ -5.49 & 35.54 \end{bmatrix}$

[1]Observed values at WHOI Site D (39°9.7' N, 69°57.1' W) for 12/12/71 to 3/5/72 (Tarbell and Whitlach, 1977).